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Mars Science Laboratory Thermal Control Architecture

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ABSTRACT

The Mars Science Laboratory (MSL[1]) mission to land a large rover on Mars is being planned for Launch in 2009. As currently conceived, the rover would use a Multi-mission Radioisotope Thermoelectric Generator (MMRTG) to generate about 110 W of electrical power for use in the rover and the science payload. Usage of an MMRTG allows for a large amount of nearly constant electrical power to be generated day and night for all seasons (year around) and latitudes. This offers a large advantage over solar arrays. The MMRTG by its nature dissipates about 2000 W of waste heat to produce 110 W of electrical power. The basic architecture of the thermal system utilizes this waste heat on the surface of Mars to maintain the rover's temperatures within their limits under all conditions. In addition, during cruise, this waste heat needs to be dissipated safely to protect sensitive components in the spacecraft and the rover. Mechanically pumped fluid loops[2] are used to both harness the MMRTG heat during surface operations as well as reject it to space during cruise. This paper will describe the basic architecture of the thermal control system, the challenges and the methods used to overcome them by the use of an innovative architecture to maximize the use of heritage from past projects while meeting the requirements for the design.

MISSION OVERVIEW

CRUISE CONFIGURATION – While the MSL mission is still in the earliest stages of its design cycle, the mission will follow the general design paradigm of the previous JPL rover missions to Mars (Mars Pathfinder, MPF[3] and Mars Exploration Rovers, MER[4]). MSL will feature a rover enclosed in an aero-shell for protection during entry and descent onto the planet's surface. A cruise stage will carry the lander and aero-shell enclosure from Earth to Mars and will separate from the lander just prior to entry, descent and landing (EDL). Figure 1 shows a rendering of the rover packed into the aero-shell enclosure with the cruise stage attached at the top.

The MMRTG is structurally attached to the rover and dissipates 2000 W of waste heat. The descent stage, containing the propulsion system and the avionics, is adjacent to the stowed rover. The cruise stage contains the avionics, propulsion system and the pumped loop radiators.

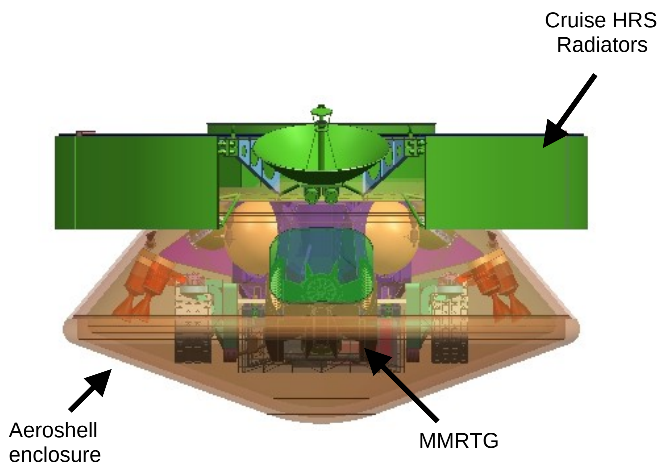

Figure 1. Mars Science Laboratory Cruise Configuration Concept

SURFACE CONFIGURATION – The surface system consists of a large rover that is capable of traversing large distances on the Martian surface. Figure 2 shows a current rendition of the deployed rover with the MMRTG attached to it.

OVERALL ARCHITECTURE

The overall system approach is to utilize mechanically pumped fluid loops for the majority of the thermal control of the rover during surface operations. The main impetus behind this is to utilize, as much as possible, the waste heat from the MMRTG to provide heat to the rover for cold conditions. Usage of electrical survival heat is minimized to allow the instruments and the avionics to partake of, as much as possible, all the electrical power produced by the MMRTG. Since the landing site will not be decided on until a much later phase of the project, the rover needs to be thermally designed to accommodate any location for any season. In other words, to design a "all terrain, all seasons vehicle." Hence, a formidable challenge is to accommodate this versatility in the thermal design created to ensure that the system works within its allowable limits for all the worst case combinations of environments and operational parameters. The range of latitudes investigated is from equatorial to +/- 60^{o}.

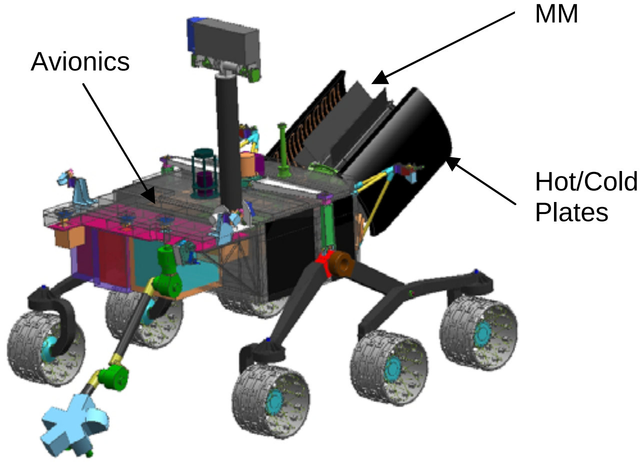

Figure 2. MSL Rover Configuration

The combination of the MMRTG waste heat and the fluid loop greatly simplifies the rover thermal design in terms of the level of thermal isolation required to maintain the rover and payload at allowable temperatures during cold conditions. It also greatly improves the robustness of the design, decouples the mechanical design and configuration from the thermal design and reduces the level of testing required.

Figure 3 shows the thermal architecture for both the surface system and the cruise pumped fluid loop system.

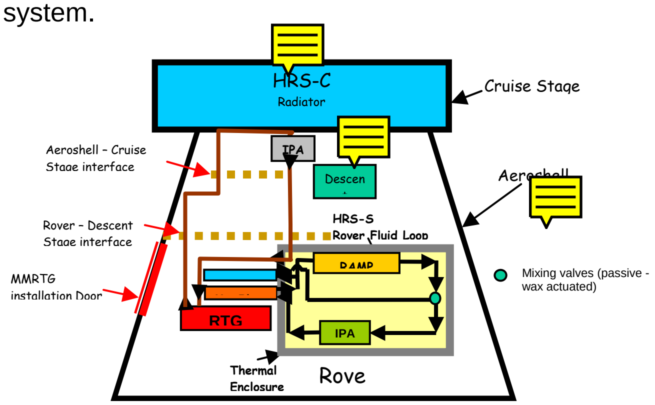

Figure 3. Overall architecture for surface and cruise pumped fluid loop systems

For the cruise system, the continuous presence of 2000 W of waste heat from the MMRTG poses a thermally difficult environment for the tightly packed spacecraft with sensitive electronics, instruments and propulsion systems adjacent to the MMRTG. A passive approach to safely dissipate all the heat from the MMRTG while maintaining its temperatures in a benign range (< ~+50 to 70 C) was investigated and abandoned because local temperatures violated allowable limits. Hence, a mechanically pumped fluid loop was base-lined to pick up the heat from the MMRTG and direct it to large radiators on the cruise stage to dissipate it to space. The heat transported is one order of magnitude larger than for the fluid loops used for Mars Pathfinder and Mars Exploration Rovers Missions[5] and the operating temperatures are much higher. This poses significant technical challenges in terms of the loop's design, qualification and implementation.

In addition to picking up heat from the MMRTG, the fluid loop also picks up heat dissipated by the rover avionics, which is approximately equal to 150 W. The temperature limits of the rover avionics are much lower than those for the MMRTG. Therefore, the fluid first enters the rover to supply the coldest fluid leaving the radiator to it before entering the MMRTG as shown in Figure 3.

Just prior to EDL the working fluid for the cruise system is vented and the cruise stage containing the pumps is separated from the lander. Disabling the pumped loop forces the MMRTG to absorb the large amount of dissipated waste heat in its own thermal mass that leads to it rising rapidly in temperature during the EDL time period of about 40 minutes. Some of this heat is dissipated passively to the heat-shield and back-shell while the MMRTG rises in temperature. Limiting the maximum MMRTG temperature during this phase and the temperature rise of the adjacent components is a challenge and requires a careful investigation of the thermal couplings between the MMRTG and the components in its neighborhood.

SURFACE OPERATIONS – A mechanically pumped fluid loop (MPFL) picks up heat from the MMRTG and supplies it to the rover avionics and payloads during cold conditions. The rover avionics and payloads are mounted on the rover avionics mounting plate (RAMP) that is thermally controlled by tubing that is part of the MPFL. The heat from the MMRTG is picked up by heat exchanger plates (hot plates) with tubing from the MPFL attached to them. Adjacent to the hot plates are cold plates that are heat exchangers and serve as radiators to reject heat from the MPFL when it is not needed by the rover (hot conditions). A passive thermal control valve (wax actuated) automatically directs flow from the hot plates to the RAMP (cold conditions) or to the cold plate radiators (hot conditions). A schematic of the surface MPFL is shown in Figure 4. A hydro-dynamically lubricated, brushless, mechanical pump circulates the fluid around the loop. These centrifugal pumps[6] have a heritage from the highly successful Mars Pathfinder (MPF) and Mars exploration Rover (MER) missions.

Figure 5 shows the physical layout of the hot and cold plates. The working fluid[7] is CFC-11 that optimizes the combinations of low freezing point, low vapor pressure, long-term compatibility with wetted materials like stainless steel and aluminum, high thermal conductivity and specific heat, low viscosity and heritage. Previous successful JPL missions (MPF & MER) utilized CFC-11.

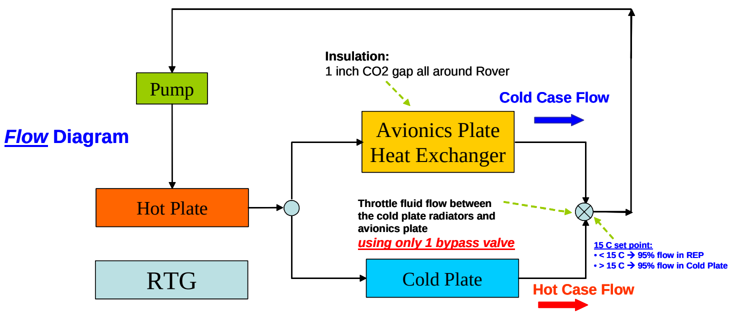

Figure 4. MSL MPFL for Surface System

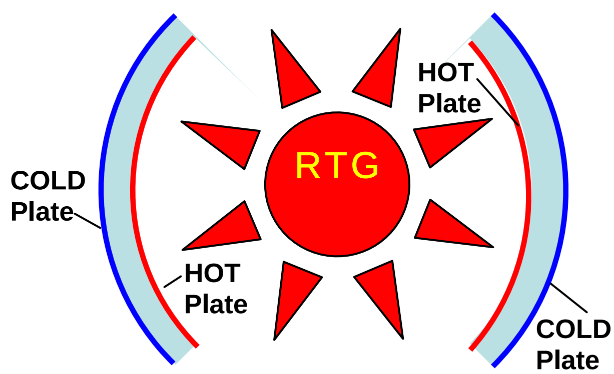

Figure 5. Surface MPFL, MMRTG and Hot/Cold Plate Configuration

As shown in Figure 4, the pump feeds the entire flow into the hot plates (viewing the MMRTG). This architecture does not bypass the flow around the hot plates during the hot conditions. This minimizes the potential for liquid boiling in the hot plates because if they were bypassed, the nearly stagnant fluid in the those locations would heat up and boil as opposed to when it is fully flowing through them. A bypass valve splits the flow leaving the hot plates between the cold plates and the avionics heat exchanger plate (in the rover) depending on its temperature.

During hot conditions, the avionics plate is bypassed (only 5% of total flow through it), whereas 95% of the total flow goes through the cold plates. The cold plates serve as radiators to reject the heat picked up from the hot plates. The CFC-11 temperature is designed to be less than about 100 C with a system pressure of about 1.36 MPa (200 psia) to prevent boiling. Since the flow through the avionics plate is bypassed during hot conditions, the avionics relies on passive heat leaks (by design) to dissipate the heat generated by the electronic components to the ambient environment (CO2, sky, ground).

During cold conditions, the paraffin actuated bypass valve diverts 95% of the flow through the avionics plates to overcome the heat loss to the very cold environment (-125 C at +/- 60^{o} latitudes). Only 5% of the total flow goes through the cold plates, thus minimizing the heat loss from them. This trickle flow of CFC-11 prevents freezing of the fluid in the cold plates while minimizing the heat losses there. The system is designed to have a 30 C margin against the freezing point (-111 C) of CFC-11. A windbreaker is located at the end of the MMRTG (the anti-rover facing side) to minimize the effects of winds, which would overcool the MMRTG and the hot plates.

The flow rate of the pumped fluid system for surface operations is about 0.75 liters per minute with a pressure drop of less than 25 kPa (4 psid). Pumps from MER heritage are used to generate this flow. The tubing is made out of aluminum with a 9.5 mm OD (3/8") and 0.9 mm (0.035") wall thickness everywhere in the loop.

For redundancy two pumps are employed. Only one pump is powered at any time. There is also a metal bellows accumulator to accommodate volume changes due to temperature changes and small leaks in the system during the mission. Check valves are used to isolate the redundant pump from the operational pump to prevent backflow. A simplified schematic of the integrated pump assembly (IPA) is shown in Figure 6. Each IPA has its own electronics to power either of the two pumps. The input power for the IPA (including the electronics) is 10 W.

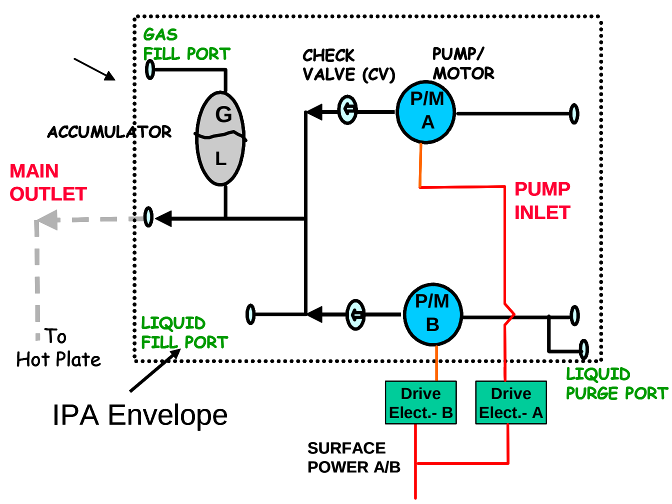

Figure 6. IPA for surface MPFL

An auxiliary assembly contains the paraffin actuated mixing valve, additional check valves and filters as shown in Figure 7. The filters protect the pump bearings from particles in the flow stream. Each filter has a check valve in parallel to allow the flow to continue (although without providing protection for the pumps) in the event of a filter saturating or clogging.

The electrical power generated by the MMRTG is not utilized for survival heat within the main body of the rover because the fluid loop performs that function. Electrical power is used for survival heat for remotely mounted payloads where it would be impractical to utilize the fluid loop due to them being mounted on moving joints.

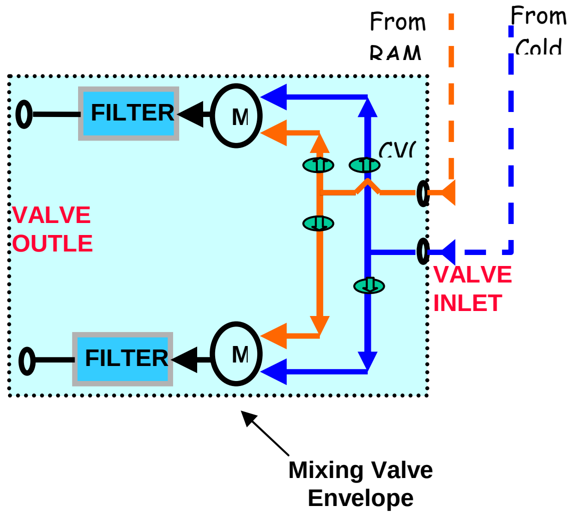

Figure 7. Auxiliary assembly for surface MPFL

CRUISE OPERATIONS – Figure 8 shows a rendering of the fluid loop during cruise operations. Since the amount of heat collected by the loop is quite large, about 2150 W, large radiators (~6 m^2) are employed to dissipate this heat to space while maintaining reasonable temperature levels in the rover and the MMRTG. The radiators constructed of 1.5 mm sheets of aluminum thermally and mechanically attached to the fluid tubing.

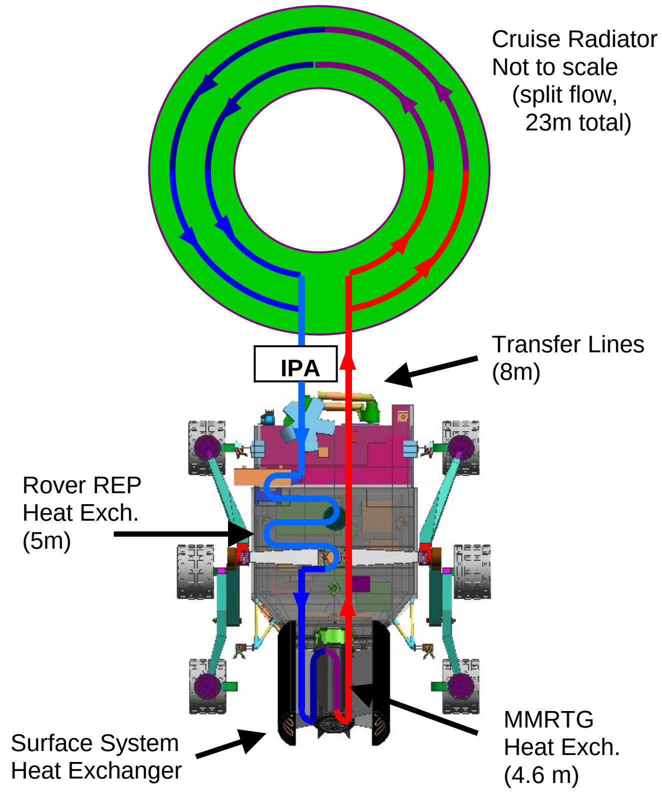

Figure 8. Cruise MPFL

The tubing is made of either aluminum or stainless steel, with aluminum being the choice where heat transfer fluxes is required (MMRTG, rover and radiator), whereas stainless steel tubing is employed for the non-heat-transfer locations (connections from rover and MMRTG to cruise stage). The rationale for this choice is based on the fact that stainless steel is much more tolerant to corrosion (with CFC-11) than aluminum is, but is not as desirable for heat transfer.

Silver/Teflon tape is utilized as the thermo-optical surface for the radiators to minimize the heat deposition on them from the sun, particularly very important since the radiators are so large and the solar loading can be a very significant fraction of the heat dissipated from them. The low absorptivity of the silver Teflon (~0.12) as opposed to 0.3 (degraded) for white paint minimizes the solar loading.

The fluid loop tubing is thermally and mechanically attached to the MMRTG fins to effectively pick up heat from it. The flow rate of CFC-11 in the cruise system is about 1.5 liters per minute with a pressure drop of less than 25 kPa (4 psid). Two IPAs from MER heritage are used in parallel to generate this flow. Each IPA contains a primary pump and a redundant pump, with only one pump operated at any time. The flow in the radiator is split to minimize the pressure drop in the system since the total length of tubing in the entire system is about 40 m with the radiator accounting for more than 50% of the length. The fin efficiency of the radiator is about 80%.

The tubing is 3/8" O.D. with 0.035" wall thickness everywhere in the loop.

EDL OPERATIONS – The MMRTG temperature during warm-up after fluid loop venting prior to EDL is restricted to < 200 C from its design limitations. The temperature of the surface fluid loop heat exchangers that face the MMRTG (hot and cold plates) is restricted to be < 100 C to prevent over-pressurization of the surface loop. The surface loop is operational during EDL (even though it is not needed during the cruise) to allow the heat arriving at the hot plates from the MMRTG to be carried to the cold plates via the surface loop flow. The thermal bypass valve in the surface system automatically directs the flow from the hot plate to the cold plate because it senses the fluid rising when the hot plate warms up during EDL. The heat from the MMRTG is prevented from entering the avionics heat exchanger because of the thermal bypass valve temperature set-point. This allows the heat from the MMRTG to be rejected to the colder back-shell and heat-shield. In addition, the heat from the hot MMRTG is directly dissipated to the back-shell and heat-shield via the view of the MMRTG in the zones not blocked by the surface system hot plates.

PERFORMANCE OF THERMAL SYSTEMS

SURFACE SYSTEM – Figure 9 shows the diurnal temperature variation of the Martian environment (CO2 at 1 kPa or 8 torr) during the worst case hot conditions. For the worst case cold conditions, the ambient atmospheric and ground temperature is essentially flat at -125 C with the sky being at -190 C.

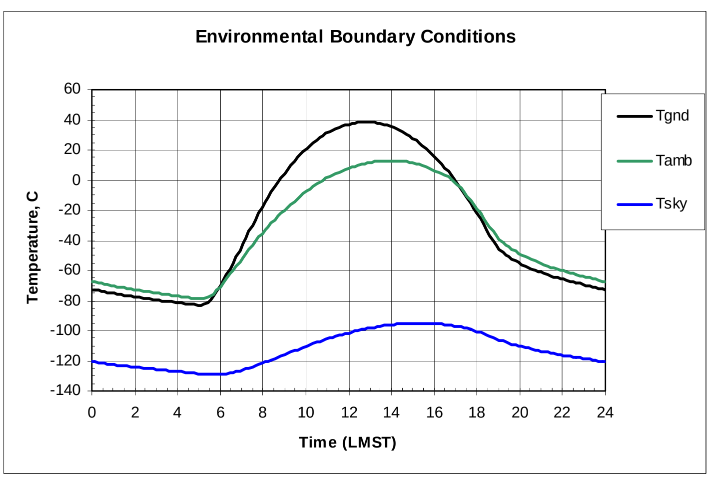

Figure 9. Diurnal environmental temperature profile at Worst Case Hot conditions on Mars

Figure 10 shows a plot of the diurnal temperature variation of the surface system avionics plate in the worst case cold conditions (60° latitude) during winter and summer. Since the environment is constant (no sun) the variation is small – on the order of < 15 C - primarily due to the power dissipation profile. This small diurnal temperature range is also very attractive in terms of ensuring long life of the electronics when subjected to many cycles on Mars. The minimum temperature of the interfaces is > - 25 C, which provides margin against the minimum flight allowable temperature of -40 C.

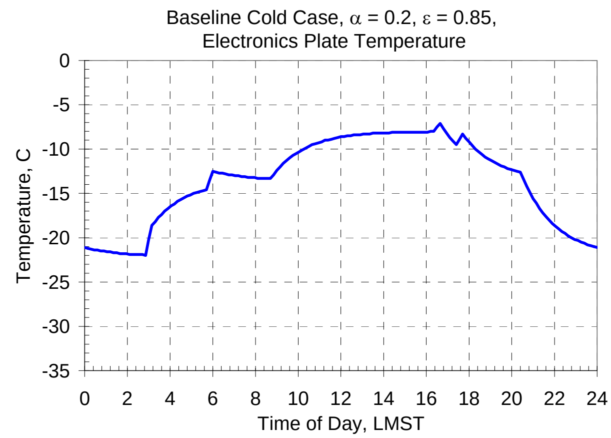

Figure 10. Diurnal temperature variation of avionics plate during worst case cold conditions

For the worst case hot conditions (15° S of equator), figure 11 shows the corresponding diurnal plot. Since the environmental temperature varies a lot, the avionics/payload temperature varies much more than the corresponding cold case. The diurnal plate temperature variation is only about 20 C, because the fluid loop supplies heat during the night to dampen out the environmental fluctuations. The maximum temperature of the electronics interfaces is about 30 C, which provides a margin of about 20 C against the maximum flight allowable even for the worst case hot conditions. In general, it is desired to keep the diurnal plate temperature fluctuation less than 60 C, which is satisfied by predictions for both the very worst case cold and hot conditions.

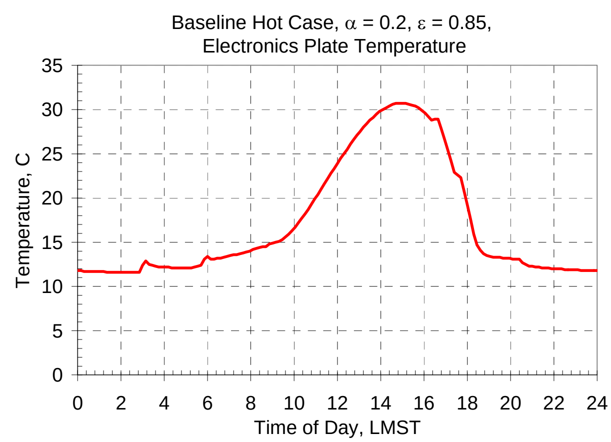

Figure 11. Diurnal temperature variation of avionics plate during worst case hot conditions

The maximum predicted CFC-11 temperature in the system (in the hot plate) is about 100 C when the fluid leaving the hot plate bypasses the avionics plate and flows entirely through the cold plate (radiator). This provides a 30 C margin against boiling in the hot plate. Similarly, the minimum predicted CFC-11 temperature in the cold plate (worst case cold conditions, cold plate bypassed) is about -85 C that provides approximately a 30 C margin against freezing.

A Computational Fluid Dynamics (CFD) modeling effort was undertaken to understand the effect of wind on the complex geometries of the Rover, MMRTG and the heat exchangers around the MMRTG. The Martian pressure of 1 kPa (8 torr) and a maximum wind speed of 15 m/s was utilized for the worst case cold analyses. The CFD analysis yielded results that required the design to incorporate a wind-breaker at the MMRTG end, as described earlier. This wind-breaker alone is sufficient to protect the MMRTG and the heat exchangers around it from the wind blowing from any direction.

CRUISE AND DESCENT SYSTEM – During cruise the CFC-11 coming out of the radiator for the cruise fluid loop is at a temperature of about 10 to 15 C in the worst case hot environment (near earth). It first enters the rover avionics plate where it picks up about 150 W of heat. It then enters the tubes in the MMRTG fins and picks up a large fraction of the MMRTG waste heat (~80% of the 2000 W), exits the MMRTG at about 70 C and rejects it to the cruise radiator. The rest of the heat from the MMRTG (20% of 2000 W) is dissipated parasitically from the MMRTG by radiation to the colder back-shell and the heat-shield. The temperature of the radiator itself is about 20 C lower than the fluid.

A detailed computer model of the cruise stage and the descent stage was constructed using the thermal software TMG (Thermal model Generator). This allowed for the calculation of the temperatures of all the components controlled by the fluid loop as well as the components utilizing more conventional means like heaters, thermostats and multilayer insulation.

A snapshot of the cruise thermal model nodalization is shown in Figure 12. The IPA for the cruise fluid loop is attached to the cruise stage. The propulsion system (tanks and lines) use conventional methods of thermal control (MLI, heaters, isolators, supports, and thermostats). The TMG model predicts that adequate maintenance of temperatures of these components within their allowable ranges do not pose any major challenges.

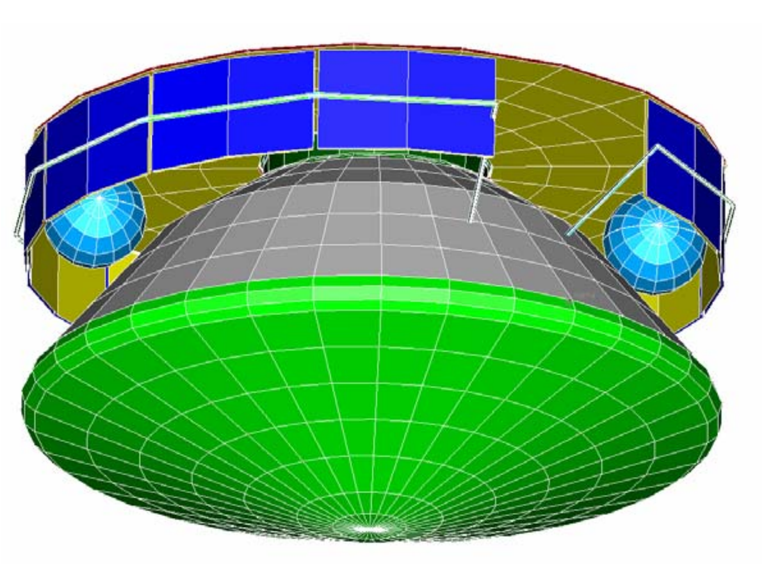

Figure 12. Thermal model of cruise system

The MMRTG is maintained at the 50 to 75 C range throughout the cruise by the fluid loop. The detailed nodal network (TMG based) for the descent stage system is shown in Figure 13. Again the TMG model predicts that all the components within the descent stage should be maintained within their allowable limits with standard thermal engineering methods as long as the fluid loop maintains the MMRTG temperatures within the range mentioned earlier.

EDL OPERATION – Just prior to EDL the CFC-11 is vented from the cruise fluid loop using a venting scheme identical to that employed in MER. Fundamentally, a pyrotechnically actuated valve inserts the gas in the accumulator in the liquid side of the fluid loop, which in turn pushes the liquid out to space via a nozzle that is opened by an additional pyro-valve. The nozzle is located at the top of the cruise stage with its opening directed along the spacecraft spin axis away from the spacecraft. This minimizes the nutation on the spacecraft during the vent process.

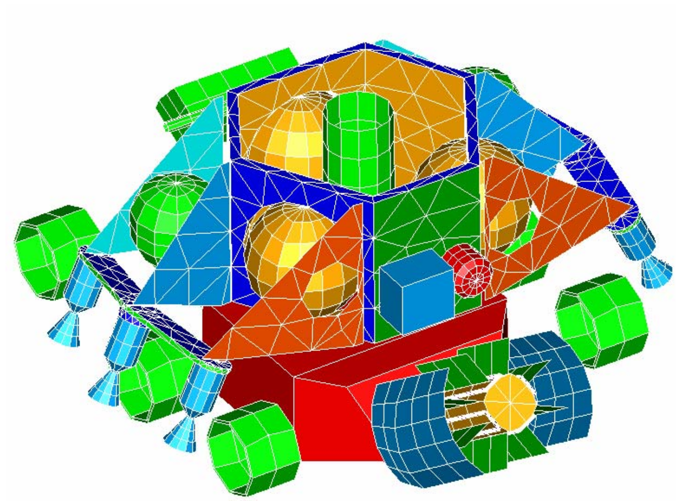

Figure 13. Thermal model of descent system

This venting leads to a rapid warm-up of the MMRTG during EDL. A sample plot of the temperature rise of the MMRTG and surrounding heat exchangers is shown in Figure 14. The current time allocation for EDL (from start of fluid loop vent to final touchdown) is about 40 minutes. For the current design in which the heat shield is covered with MLI and has no MLI on the back shell, the TMG model predicts that MMRTG temperature will be lower than its limit of 200 C during EDL. The corresponding temperature of the MMRTG heat exchangers (for the surface fluid loop) are also well within their temperature limit of 100 C during EDL.

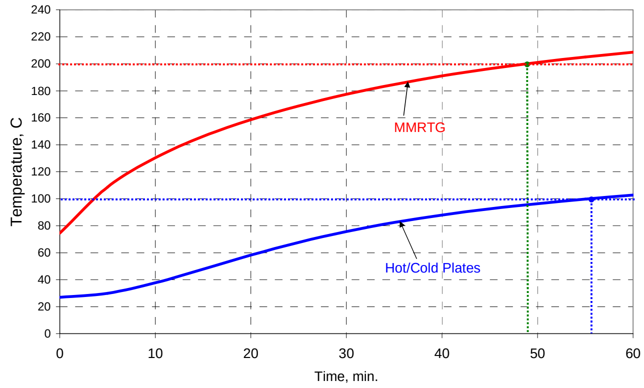

Figure 14. Post MPFL venting warm-up of MMRTG and MMRTG heat exchangers

HIGH TEMPERATURE FLUID LOOP (MPFL) DEVELOPMENT TESTS[8]

As mentioned earlier, the fluid chosen for both the cruise and the surface systems is CFC-11. Both the MPF and MER missions were designed to subject the CFC-11 to temperature no higher than about 50 C. For MSL, due to the constraints imposed by the designs of these loops in the presence of the MMRTG, the corresponding highest temperature is about 100 C. Since the earlier development tests and heritage of these missions did not provide data on the long term compatibility of the loop components at elevated temperatures with CFC-11, a sleuth of development test have been undertaken to retire any risks associated with about 1 to 3 years of operation of these loops at elevated temperatures.

Three kinds of test are being conducted: 1) component, particularly at the tubing level, compatibility with CFC-11 at 100 C; 2) long term operation of the pump at 100 C, while wetted by CFC-11; and 3) a full up long term life test that simulates all the components and subsystems in the fluid loops, with appropriate representation of sizes in the flight system, to understand the synergistic effect of all these subsystems working together in the flight system.

COMPONENT TESTS - The initial development process for the MPFL system involves identifying candidate loop components, performance/functional testing of these components at elevated temperatures, and material compatibility studies. It is expected that the high temperature MPFL system for the Mars Science Laboratory mission will incorporate many of the same components that comprised the cruise stage heat rejection systems on MPF and MER spacecraft. These components include one or more mechanical pumps, a thermally actuated bypass valve, a fluid accumulator, filter, tubing, radiator heat exchanger, and fluid venting system. Laboratory development tests are being used to uncover any potential problems related to the elevated operational temperature range and to suggest potential solutions or design changes. Several samples of tubing that represents all the materials in the flight system that are wetted by the CFC-11 – aluminum, stainless steel and interface joints between these two – are filled with CFC-11 and kept at 100 C in an oven. Periodically these tubing are removed and analyzed (CFC-11 as well as metal) to understand the long term trend of any degradation of either the fluid or the metal.

HIGH TEMPERATURE PUMP TESTBED - The first development test initiated under this effort is a high temperature pump testbed. A centrifugal pump of the same design to the one flown on the MER mission and baselined for the MSL mission was designed by Pacific Design Technologies, Inc. for this test. The pump is made of 300 series stainless steel and was designed to operate with CFC-11 as the working fluid at a maximum operating temperature of 100ºC. The pump is capable of delivering up to 0.75 liters per minute of water at this maximum temperature while incurring a pressure drop of less than 25 kPa (4 psid.) For this testing effort, the pump was designed with O-ring seals and metal fasteners so that it could be disassembled and inspected before and after tests.

A high temperature test setup was constructed to monitor the performance of the pump under a continuous environmental temperature of 100ºC. Figure 15 shows a schematic of this setup. The testbed is largely comprised of 9 mm OD (3/8”) stainless steel tubing and has a large number of valves to allow individual component isolation from the rest of the loop. A series of sample coils and valves are placed in the loop to allow the effective length of the flow path to be altered. A dual valve assembly at the base of each coil permits its removal without disrupting the test in progress. A stainless steel filter is placed in the loop to remove all particles greater than 25 microns from the flow. This filter may be disassembled after a test has been completed to access and analyze trapped particulate material. A stainless steel sample cylinder is positioned vertically and pressurized with gaseous nitrogen to serve as a fluid accumulator. A photograph of the test setup is shown in Figure 16.

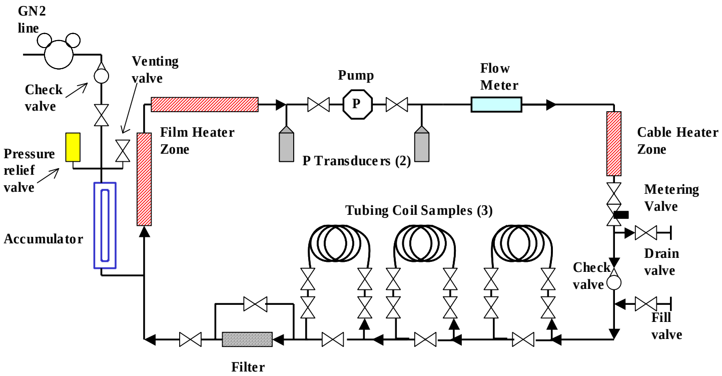

Figure 15. Schematic of high temperature test setup for pumped loop

Figure 16. Hgh Temperature Pump Testbed

In addition to performance testing, the long term material compatibility of the components in the high temperature MPFL system are also being monitored. Although the system was designed using materials compatible with CFC-11 systems (e.g. stainless steels, Teflon), high temperature CFC-11 can be an aggressive solvent. Thus, to observe possible corrosion in the system, the CFC-11 in the test loop will be periodically sampled and tested for particulates, anions, and dissolved metals.

CONCLUSION

The MSL mission utilizes a mechanically pumped fluid loop based architecture to provide thermal control of the spacecraft and its rover during cruise as well as surface operations. The architecture harnesses waste heat from the MMRTG during surface operations and safely rejects this heat during cruise. This architecture is well suited for this mission due to the unique challenges posed by the MMRTG. Several kinds of development tests are being conducted to retire any risks associated with extending the boundaries of earlier highly successful missions that utilized fluid loops (MPF, MER). Since MMRTG based systems are being envisioned for future missions after MSL, development and successful demonstration of these advanced technologies will serve as pathfinders for these future missions.

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ACRONYMS

HRS: Heat Rejection System
JPL: Jet Propulsion Laboratory
MER: Mars Exploration Rover
MLI: Multilayer insulation
MPF: Mars Pathfinder

MPFL: Mechanically Pumped Single-phase Fluid Loop
MSL: Mars Science Laboratory
NASA: National Aeronautics and Space Administration
NSTS: National Space Transportation System
MMRTG: Radioisotope Power Source
RTG: Radioisotope Thermo-electric Generator